Experimental Centrifuge Testing and Analytical Studies of Particle Damping Behavior

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ABSTRACT

In this paper, analytical and experimental studies of particle damping behavior are discussed. These studies have focused on the development of an analytical model to predict particle damping behavior and on determination of the effects of centrifugal loading on the behavior. An analytical model, based on the particle dynamics method, has been developed and is being correlated with results from experimental testing. A novel test facility is being established which enables laboratory based evaluation of the damping effectiveness of blade-like objects under centrifugal loading. Depending on the test article, this facility will be capable of exposing test specimens to centrifugal accelerations of up to 124,000 G's.

1. INTRODUCTION

Particle damping is a derivative of impact damping where multiple auxiliary masses of small size are placed inside a cavity attached to the vibrating structure. Particle damping is one of few passive damping techniques with the potential to function under the extreme temperatures and centrifugal loading seen in the turbine engine environment. However, a comprehensive design methodology for particle damping needs to be developed and the ability of particle dampers to function under centrifugal loading requires further examination. An analytical model to predict the effectiveness of particle damping has been developed. In addition, a laboratory based centrifuge test system has been constructed which will allow rapid testing of various damping systems under actual centrifugal loading and controllable dynamic excitation. Analytical and experimental efforts are discussed in the following paragraphs.

2. PARTICLE DAMPER MODELING

Studies conducted over recent years have demonstrated the effectiveness and potential application of particle dampers, and have shown that particle dampers are highly nonlinear dampers whose energy dissipation, or damping, is derived from a combination of loss mechanisms. The relative effectiveness of these mechanisms changes based on various system parameters. Due to the complex interactions involved in the particle damper, a comprehensive design methodology has not been developed which will allow particle damping technology to be implemented without extensive trial-and-error testing. One of the first steps in the development of a comprehensive design methodology is to develop an analytical model to predict particle damper behavior.

An analytical particle damper model has been developed based on the particle dynamics method. The particle dynamics method is a technique where individual particles are modeled and their motions tracked in time. This technique is similar to that used for modeling molecular dynamics and is useful for considering effects such as surface friction, collisional energy losses, boundary

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**
4. TITLE AND SUBTITLE **Experimental Centrifuge Testing and Analytical Studies of Particle Damping Behavior**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **CSA Engineering Inc,2565 Leghorn St,Mountain View,CA,94043**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

forces, and gravity. Much of the pioneering work using the particle dynamics method to simulate the behavior of granular materials was performed by Cundall and Strack [1-4]. Salueña, *et al.* [5] demonstrated that the particle dynamics method could be used to evaluate the dissipative properties of granular materials.

The particle dynamics method is an explicit process with sufficiently small time steps taken such that during a single time step disturbances cannot propagate from any particle further than its immediate neighbors. As a result, at a given time, the resultant forces on any particle are determined exclusively by its interaction with the particles with which it is in contact. This feature makes it possible to follow the nonlinear interaction of a large number of particles without excessive memory or the need for an iterative procedure. The utility of the particle dynamics method is based on the ability to simulate contact interactions based on a small number of parameters that capture the most important contact properties. Interaction forces between the individual particles and the cavity walls are calculated based on force-displacement relations. One of the critical aspects for developing an accurate mathematical model is the selection of appropriate force-displacement relations to account for the forces created due to particle-particle impacts and due to particle-cavity impacts.

Force-displacement relations have been incorporated in the model for both normal and shear forces. The normal force relations use a modified form of relations proposed by Lee and Radok [6] and incorporate both elastic and dissipative portions of the normal force. An incremental form of the relations is used and the particles can be given elastic or viscoelastic material properties. For elastic properties, the normal force-displacement relation reverts to an incremental form of Hertz's law. Viscoelastic material properties are given as a three-parameter Maxwell model. The incremental form of the force-displacement relation incorporates the relaxation behavior of the viscoelastic material.

Shear forces are implemented in the model based on Amonton's law of friction (Coulomb friction). Currently, only a single kinetic coefficient of friction is given for particle-particle and particle-cavity contact. The magnitude of the shear forces is based solely on the magnitude of the normal force and the coefficient of friction. The direction of the shear force opposes the relative tangential velocity between the contact surfaces. Relative tangential velocities can result from oblique impacts or due to rotation of the particles.

When particles collide with the cavity walls, particle-cavity force displacement relations are required. The particle-cavity relations have been formulated by modifying the particle-particle relations to account for the material properties of the cavity and the local curvature. For simplicity, initially it has been assumed that the cavity walls are flat and rigid.

The background of the particle damper simulation code is based on X3D, an explicit finite element code typically used for impact analyses [7]. The code contains various contact algorithms and bookkeeping routines and provides an appropriate framework for simulating particle damping through the use of the particle dynamics method. Particle-particle and particle-cavity contacts are resolved using the force-displacement relations discussed above.

Experimental testing of a cantilevered aluminum beam incorporating particle damping has been performed in the absence of centrifugal loading using the test setup shown in Figure 1. The first bending mode of the beam is excited harmonically near the root of the beam through a nylon stinger attached to a 50 pound shaker. Accelerations at the tip of the beam are measured using an accelerometer and used to calculate beam tip displacements. Dampers are placed near the tip of the beam where the largest displacements are observed for the first bending mode.

Analytical predictions corresponding to various experimental test cases have been made using a version of the X3D code modified for particle damper simulations. The aluminum beam used for the experimental testing is modeled as a lumped mass attached to a damped spring-to-ground element. The mass, spring stiffness, and damping are chosen to simulate the undamped beam. The cavity is modeled using contact surfaces defined by nodes which are linked to a master cavity node. The beam system is excited by a prescribed sinusoidal force applied to the master cavity node. Particles are tracked using a node at the center of each particle.

Current efforts are focused on correlating analytical predictions to experimental test results. Figure 2 shows experimental and analytical results for the undamped aluminum beam and for the beam with particle dampers containing a single 0.250 inch diameter steel sphere with a clearance of 0.005 inch and with the steel sphere replaced with (64) 0.0625 inch diameter steel spheres. Predicted results for a beam with an added mass identical to that of the two dampers also are included. Two sets of results are given for the damper containing (64) 0.0625 inch diameter steel spheres. The first set of results (from ss003a) was taken with the excitation frequency increasing and the second set (ss004a) with the excitation frequency decreasing. Differences between these two results indicate that friction may significantly affect the damper behavior and illustrate some of the complex behavior which may occur with particle dampers. The analytical results shown in Figure 2 do not include friction, but include viscoelasticity in the steel material model. Additional particle damper simulations are being performed.

Although correlation efforts under 1 G loading are continuing, preliminary simulations have been performed to investigate the influence of centrifugal loads on the behavior of the damper. Figures 3 through 5 show selected frames from simulations with (64) 0.0625 inch diameter steel spheres under centrifugal loads of 1 G, 10 G's, and 100 G's, respectively. Although these G levels may seem small relative to the loads seen in the turbine engine environment, the critical relationship is the ratio of the vibratory accelerations to the centrifugal accelerations. For these simulations, the vibratory acceleration was slightly less than 10 G's, resulting in vibratory to centrifugal acceleration ratios of approximately 10, 1, and 0.1, respectively.

Under 1 G gravity loading, considerable particle motion is predicted within the cavity and a large attenuation in the beam response is predicted. These results compare well with the particle behavior observed in the laboratory and measured attenuations. As the centrifugal load is increased, particle motion decreases and, as a result, the attenuation in the beam response decreases. For the damper shown in Figures 3 to 5, the damper essentially "turned off" under a centrifugal load of approximately 100 G's, or a vibratory to centrifugal acceleration ratio of approximately 0.1. Further discussion on the importance of these ratios will be given in the following experimental centrifuge testing section.

3. EXPERIMENTAL CENTRIFUGE TESTING

The critical issue with regards to the effectiveness of particle damping under centrifugal loads is the ability of the particle damper to function under centrifugal loads. Such loads can easily exceed 10,000 G's at locations where particle dampers would likely be integrated into a blade. While some researchers have seen damping with single particles under centrifugal loads [8-10], others [11] have only seen limited effectiveness with multiple particles. Closer inspection of the test procedures has revealed that, for most testing performed under centrifugal loads, the disturbance excitation levels and the ratios of these excitation levels to the centrifugal loads are less than those which would be expected in an actual blade at full rated speed. Figure 6 shows a plot of the excitation to centrifugal acceleration ratio versus the centrifugal acceleration. Included on the plot are results from experimental testing performed at NASA Glenn [9-10], experimental testing previously performed during [8] and planned for future testing, and results found in the open literature which discuss the typical ratios and accelerations experienced by turbine engine blades. Note that during the experimental testing labeled Phase I STTR, the excitation to centrifugal acceleration ratios were generally much less than the 0.1 ratio that turbine engine blades typically experience. Preliminary analytical predictions also indicate the damping may "turn off" somewhere around 0.1.

To permit experimental testing at acceleration ratios and centrifugal loading which are more representative of those expected in actual blades, a novel test facility is being established which will enable laboratory-based evaluation of the damping effectiveness of treatments on blade-like objects under centrifugal loading. Depending on the test article, this facility is capable of exposing test specimens to rotational speeds of up to 24,000 rpm or to centrifugal accelerations of up to 124,000 G's. The facility is based on a medical centrifuge which has been modified to incorporate the test hardware required. Examples include a custom hub, blade and counterbalance, 10 channel slip ring, internal vacuum sensor, cable bundles, etc. Figure 7 shows the centrifuge and some of the hardware for this new facility. Excitation of the blade-like test specimens is accomplished using piezoelectric patches to achieve excitation levels greater than those seen in previous testing. For the hardware shown, the facility will be capable of exposing candidate damping treatments to centrifugal loads between 180 G's and 65,000 G's (initially limited to 5700 G's due to the on blade accelerometers) in a vacuum environment, with user controllable out-of-plane excitation accelerations of between 0 G's and 250 G's. The test facility is suitable for performing the types of testing required to evaluate particle damping and other damping systems proposed for use in blades. Testing can be performed relatively inexpensively and quickly in a laboratory environment.

4. CONCLUSIONS

Preliminary experimental damping measurements have been made for a cantilevered beam system incorporating particle damping. Results from this testing demonstrate some of the challenges in predicting the highly nonlinear behavior of particle dampers. An analytical model to predict particle damping has been developed. Correlation between preliminary experimental and analytical results is encouraging. Further investigation into the effects of centrifugal loading on particle damping behavior are required. Previous experimental testing has shown mixed results; however, most testing has been performed at vibratory to centrifugal acceleration ratios which are much less than those expected in an actual turbine engine blade. Additional experimental testing under centrifugal loads is planned. This testing will utilize the novel, laboratory-based centrifuge test system which has been developed under this efforts.

5. AKNOWLEDGEMENTS

The work discussed is being performed under an STTR Phase II effort for the U.S. Air Force Research Laboratory entitled "Centrifugally Loaded Particle Damping," Contract No. F33615-98-C-2885. The authors gratefully acknowledge the support and guidance of Mr. Frank Lieghley, the project technical monitor for this effort.

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Figure 1. Experimental test setup

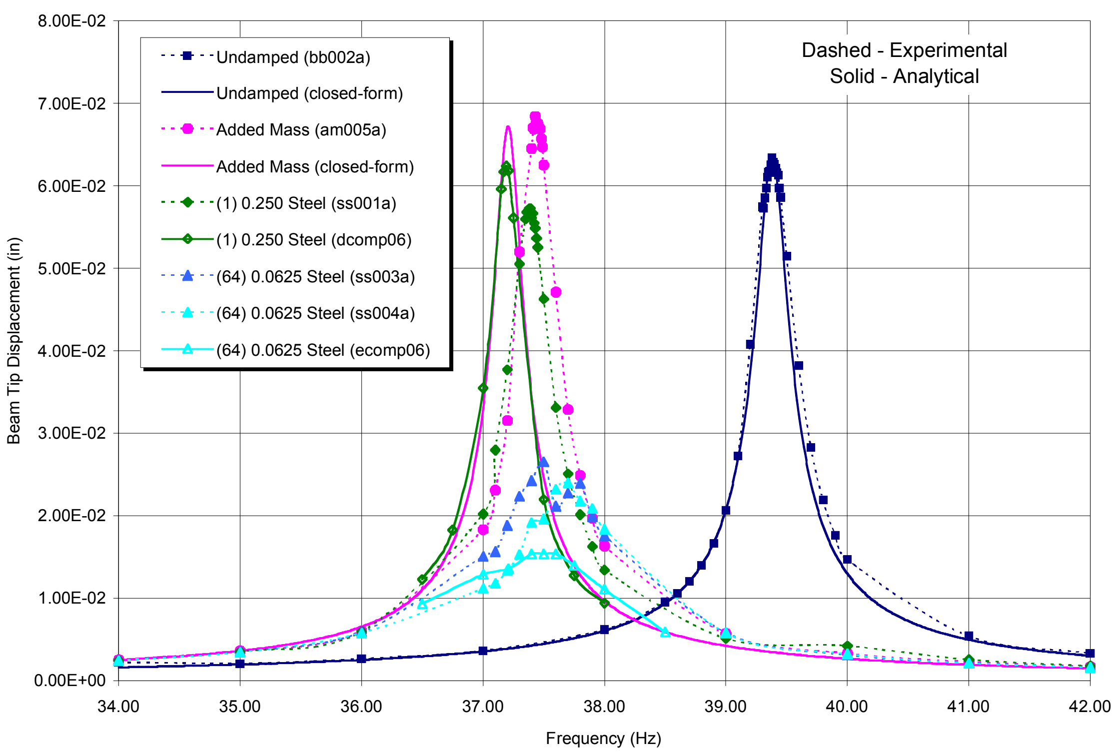

Figure 2. Comparison of preliminary experimental and analytical results

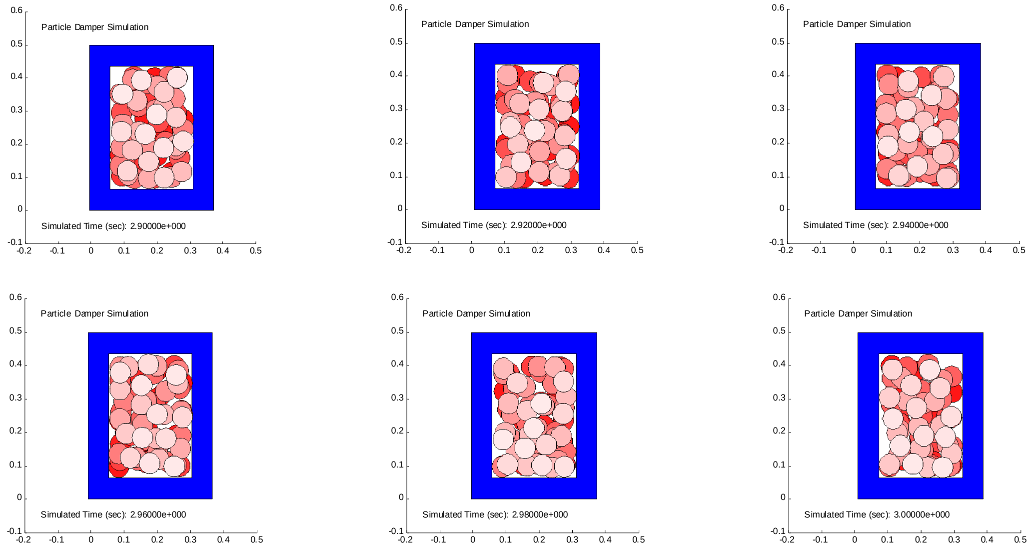

Figure 3. Selected frames from particle damper simulation under 1G load

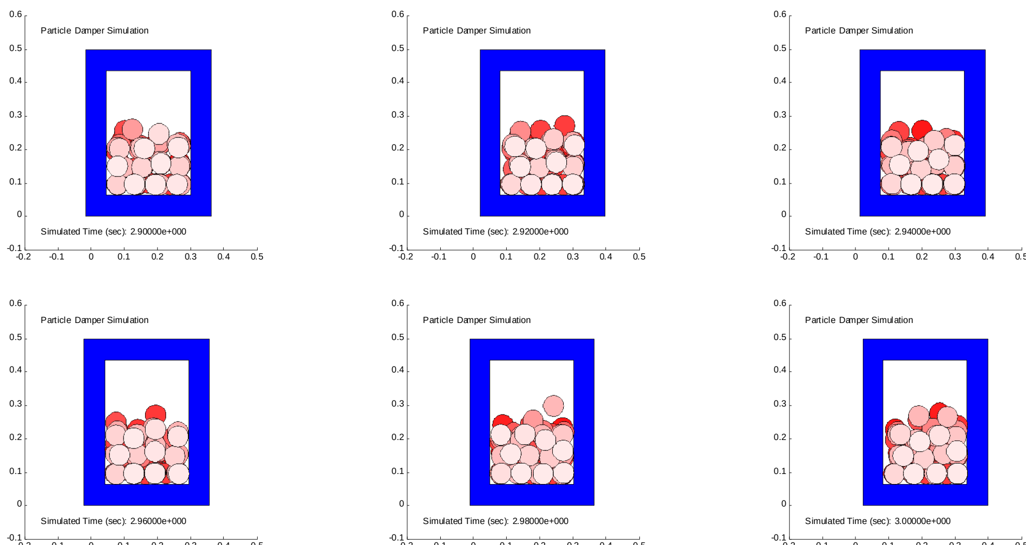

Figure 4. Selected frames from particle damper simulation under 10G load

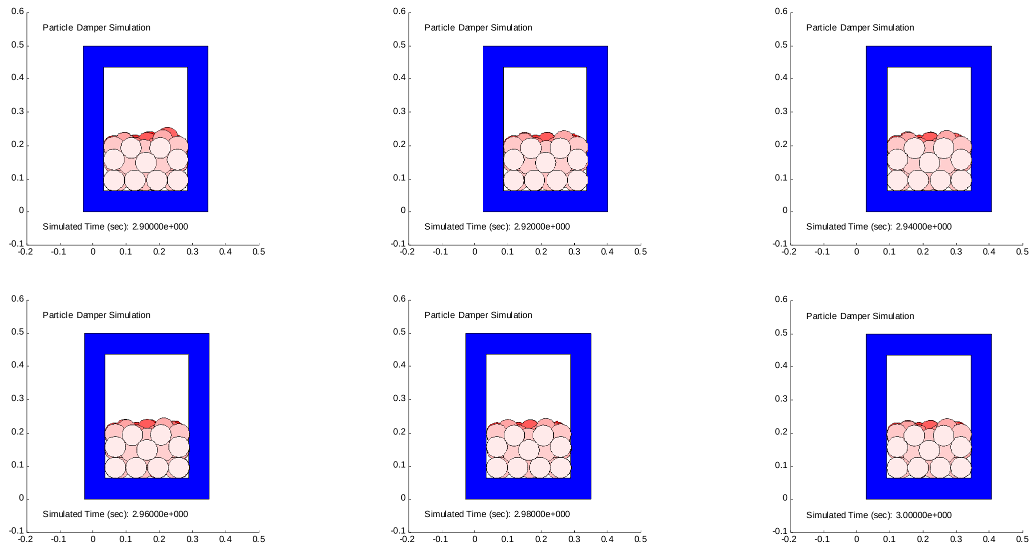

Figure 5. Selected frames from particle damper simulation under 100 G load

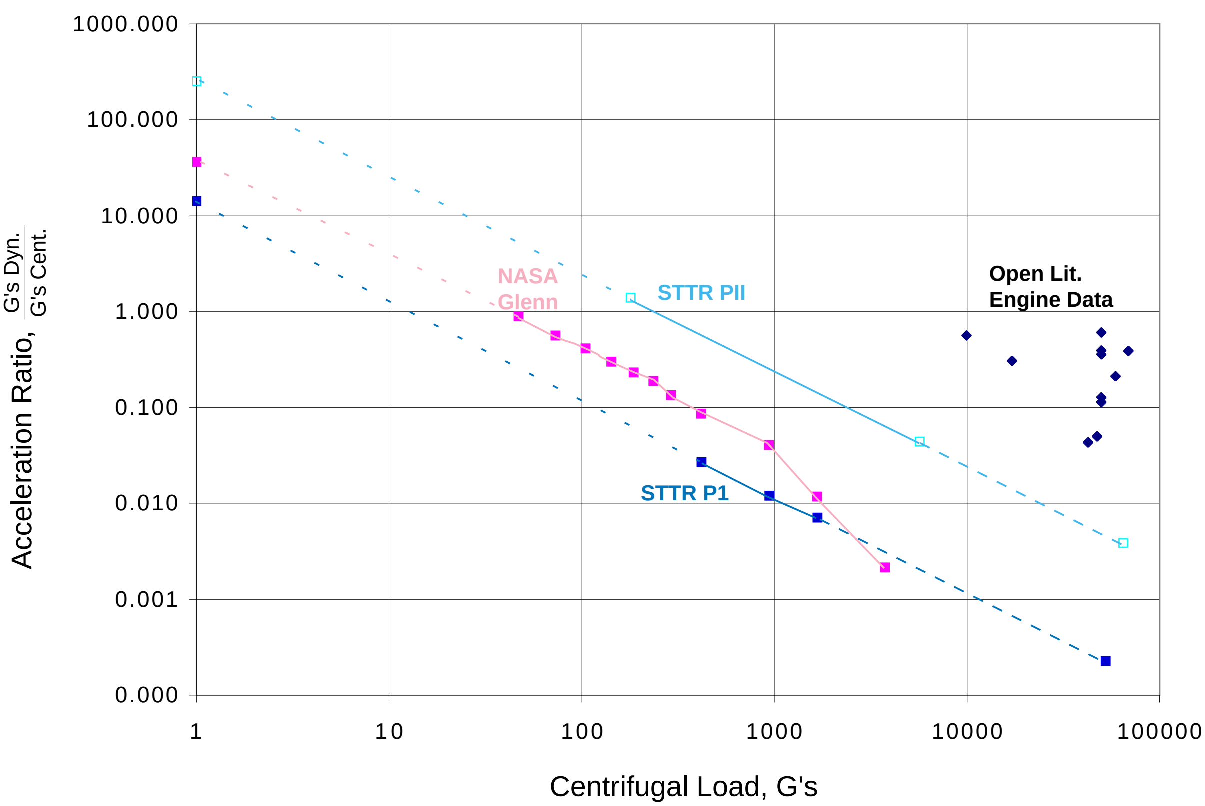

Figure 6. Acceleration ratio versus centrifugal acceleration